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A Review on Abrasive Flow Machining (AFM)

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Abstract

The required finish/texture is one of the prime requirements in various, finished components through conventional machining, processes like grinding, lapping, polishing and super finishing processes. Industries are spending huge amount of money to get the required finish and texture after the components being machined. This will calls for advanced non conventional finishing processes. Abrasive Flow Machining (AFM) is one of the non conventional finishing processes in which a semi-solid medium consisting of a visco-elastic polymer and abrasive particles mixed in a definite proportion. This media is extruded under pressure through or across the surface to get the required finish. In this article an attempt has been made to review various published technical papers on AFM and segregated into four categories - experimental setups, abrasive media, modeling and optimization and applications. The review paper opens new research avenues for further work.

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*Keywords:*Non-conventional machining; abrasive flow machining; viscoelastic polymer; miniaturized product; modeling; optimization;

1. Introduction

A rapid development in engineering and technology needs high accuracy and high precise miniaturized products. Surface quality of products plays major role in automotive, aerospace and biomedical industries. A small burrs or scratch will cause big loss such as energy loss in engine, failure of aerospace devices, malfunctioning of components etc. Industries are striving hard and spending huge amount on finishing of these components to make burrs/cutting marks free components. From the past four decades industries are using the traditional type of finishing processes

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like grinding, lapping and honing etc to get the required finish on the machined components. But these traditional finishing processes are limited to particular geometries and cannot be applicable to complex geometries and intricate profiles to machine to high level finish as required during the operation of these components. Limitations of the traditional finishing processes leads to development of advanced finishing processes - Abrasive Flow Machining (AFM), which is used to machine the difficult-to-machine internal features in engineering materials like non-ferrous alloys, superalloys, ceramics, refractory materials, carbides, semiconductors, quartz, composites etc. that cannot be machined by the conventional machining processes efficiently and economically. The objective of this process is to produce nano level finish on the machined components which is need of the time. Extrude Hone Corporation of USA in 1960s developed the concept of AFM to finish aerospace components to the required accuracy. Today abrasive flow machining is considered as one of the best method for finishing of complex geometries not accessible by the conventional finishing tools. Many researchers are constantly trying to improve the performance of AFM process. This review article provides an insight into the recent developments in the experimental setups, abrasive media, modeling and optimization and promising application areas.

2. Experimental setup

Major components of the abrasive flow machine include machine itself, tooling and abrasive medium [1]. The material removal mechanism includes three deformation modes– elastic deformation, plastic deformation or plouging and micro cutting of material. These deformation modes are strongly depends on the magnitude of cutting forces acting on an individual abrasive grain and depth of indentation of abrasive in the workpiece [2]. Fig. 1 shows the material removal mechanism of AFM process.

Based on the motion of abrasive media, abrasive flow machines are classified into three types:

1. One-way AFM: Abrasive media is pushed in one direction as shown in Fig. 2 (a) [3].
2. Two-way AFM: Abrasive media reciprocates to and fro as shown in Fig. 2 (b) [4].
3. Orbital AFM: Small orbital vibrations are applied to the workpiece as shown in Fig. 2 (c) [5].

Williams and Rajurkar have identified the AFM process mechanisms [6]. They have developed the modelling of surface generation and online monitoring system to monitor the AFM process. Experimental investigations have been carried out by many researchers to identify the influencing factors of the process [7, 8, 9, 10, 11,12]. Table 1 shows AFM process parameters used.

Table 1. AFM process parameters.

Machine	Medium	Workpiece
• Extrusion Pressure • Number of Cycles	• Rheological properties of Media • Type of Abrasive • Abrasive Mesh Size • Concentration of Abrasives and Carrier • Type of Polymer Carrier • Additives	• Material • Hardness • Geometry • Initial Surface Finish • Surface Texture

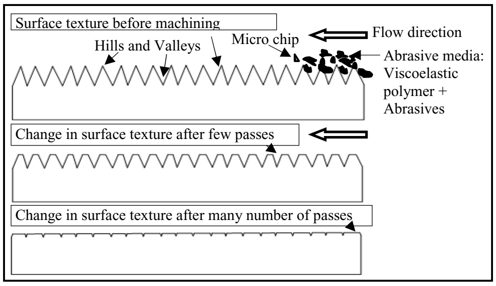
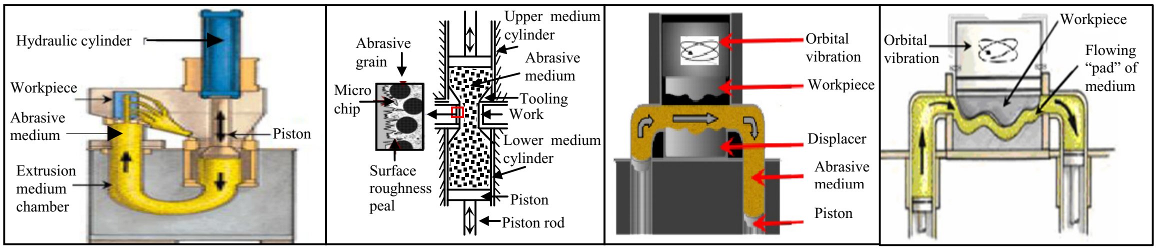


Fig. 1. Material removal mechanism of AFM process.



(a) One way AFM process (b) Two way AFM process (c) Orbital AFM - before finishing and while finishing

Fig. 2. Types of abrasive flow machine [6].

Researchers have reported AFM is a slow process because of the total time to achieve the required finish is longer and material removal rate is lower. To enhance the performance of AFM process many researchers are developed the hybrid machining processes in which various machining processes are combined with AFM process to achieve the higher MRR and required surface finish in lesser time. Some of the recent developments in hybrid AFM processes are presented in this section.

Singh and Shan [13] developed Magneto Abrasive Flow Machining (MAFM) process to improve the material removal rate and reduces surface roughness by applying a magnetic field around the workpiece. ANOVA technique has been used to identify the most significant parameters - magnetic flux density, volume flow rate, number of cycles, medium flow volume, abrasive grit size, abrasive concentration and reduction ratios. Improved surface finish and MRR is observed in MAFM over AFM. The schematic diagram of MAFM is shown in Fig. 3.

Jha and Jain [14] explored Magnetorheological Abrasive Flow Finishing (MRAFF) process for finishing complex internal geometries as shown in Fig. 4. In this process magnetorheological polishing fluid consists of carbonyl iron powder and silicon carbide abrasives are mixed with viscoelastic base grease and mineral oil used to finish stainless steel workpieces. No improvement in surface finish at zero magnetic field condition and 30 % improvement in surface finish at high magnetic field strength were observed. Walia et al. [15] tried to improve the performance of AFM process by applying centrifugal force on the abrasive media by introducing rotating centrifugal force generating rod in the workpiece passage. The process is termed as Centrifugal Force Assisted Abrasive Flow Machining (CFAAFM) as shown in Fig. 5. They have concluded that better surface finish is achieved due to centrifugal action caused by the rod on the abrasive media.

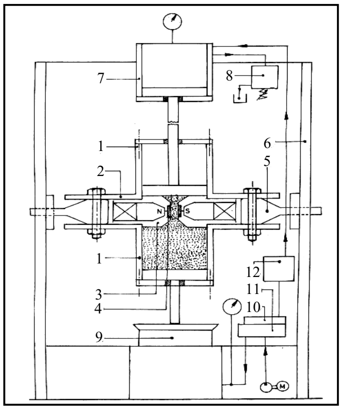


Fig. 3. Schematic diagram of MAFM.
Main parts: (1) cylinder containing medium; (2) flange; (3) nylon fixture; (4) workpiece; (5) eye bolt; (6) hydraulic press; (7) auxiliary cylinder; (8) modular relief valve; (9) piston of hydraulic press; (10) directional control valve; (11) & (12) manifold blocks; (13) electromagnet. [13].

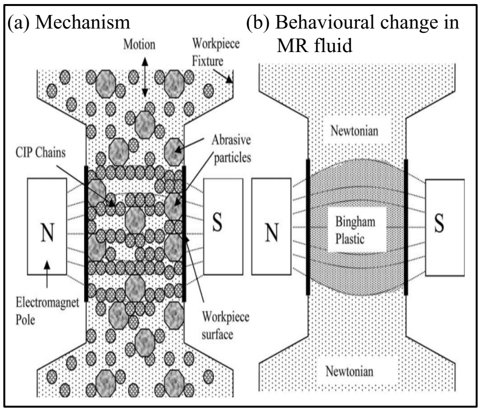


Fig. 4. Schematic diagram of MRAFF.
a) Mechanism of magnetorheological abrasive flow finishing process; b) Change in rheological behaviour of MR-polishing fluid [14].

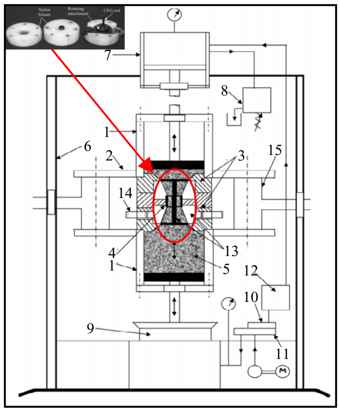


Fig. 5. Schematic diagram of CFAAFM
Main parts: (1) Cylinder containing media; (2) Flange; (3) Fixture; (4) Workpiece; (5) Abrasive laden media; (6) Hydraulic press; (7) Auxiliary cylinder; (8) Modular relief valve; (9) Piston of hydraulic press; (10) Directional control valve; (11,12) Manifold blocks; (13) Rotating CFG rod assembly; (14) Idle gear; (15) Eye bolt [15].

Dabrowski et al. [16] developed Electro-Chemical aided Abrasive Flow Machining (ECAFM) process by using polymeric electrolytes for smoothing flat surfaces as shown in Fig. 6. The ion conductivity of electrolytes is lower than the conductivity of electrolytes employed in ordinary Electro-Chemical Machining (ECM). Additions of inorganic fillers to electrolytes in the form of abrasives decrease conductivity even more. These considerations explain why the inter electrode gap through which the polymeric electrolyte is forced should be small. This in turn results in greater flow resistance of polymeric electrolyte, which takes the form of a semi-liquid paste. Polymer electrolytes as gelated polymers and water-gels based on acryloamide were used for experimental investigations.

To enhance the performance of abrasive flow finishing process Shankar et al. [17] introduced a concept of rotating medium along its axis to achieve higher rate of finish and material removal and these process is called as Drill-Bit Guided-Abrasive Flow Finishing (DBG-AFF) process as shown in Fig. 7. The experiments were conducted on AISI 1040 and AISI 4340 workpiece materials. Higher finishing rate and material removal rates are observed in DBG-AFF process compared to Abrasive Flow Finishing (AFF) process. Shankar et al. [18] developed a Rotational-Abrasive Flow Finishing (R-AFF) process. In this process a workpiece is rotated at certain speed to enhance the performance of finishing process. Experiments were conducted using central composite rotatable design and responses are plotted using Response Surface Modeling (RSM) technique. The schematic diagram of R-AFF process as shown in Fig. 8.

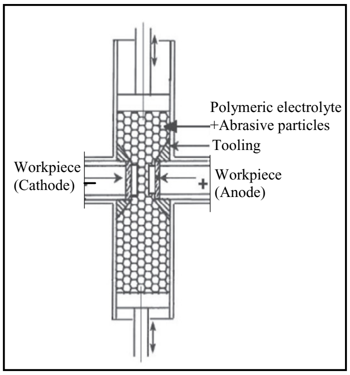


Fig. 6. Schematic diagram of ECAFM [16].

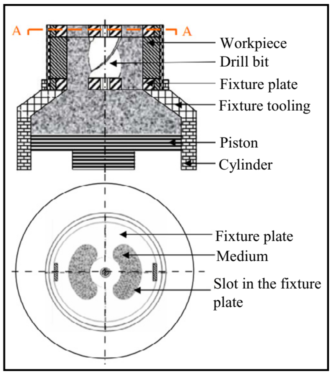


Fig. 7. Schematic diagram of DBG-AFF [17].

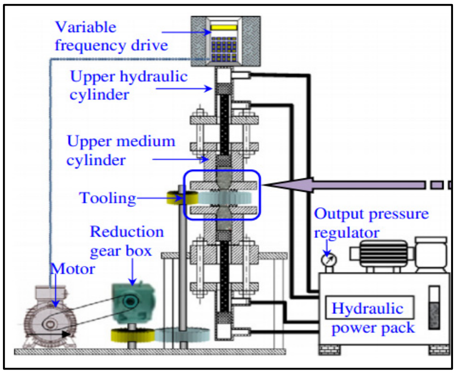


Fig. 8. Schematic diagram of R-AFF [18].

Sharma et al. [19] introduced an Ultrasonic Assisted Abrasive Flow Machining (UAAFM) process in which workpiece is subjected to ultrasonic vibration perpendicular to the media flow direction. Fig. 9. shows the schematic diagram of UAAFM process. Das et al. [20] proposed Rotational Magnetorheological Abrasive Flow Finishing (R-MRAFF) process to enhance the finishing performance of MRAFF process. In this process, a rotation and reciprocating motion is provided to the abrasive medium by a rotating magnetic field and hydraulic unit as shown in Fig. 10. Smooth and mirror-like surfaces are observed in both stainless steel and brass workpieces.

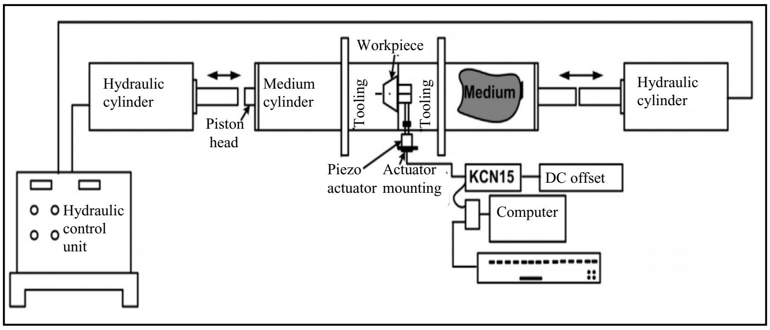


Fig. 9. Schematic diagram of UAAFM [19].

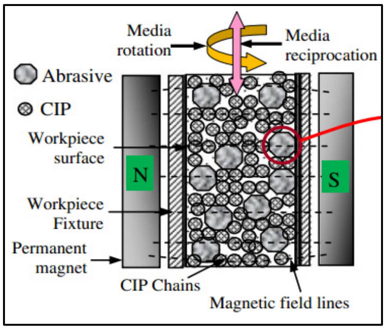


Fig. 10. Schematic diagram of R-MRAFF [20].

3. Abrasive media

Abrasive media is main constituent of the AFM process. The medium consists of viscoelastic polymer reinforced with the abrasive particles. In this viscoelastic polymer acts as a carrier medium and abrasive particles acts as a cutting tool which removes the material from the workpiece. The commonly used polymer media are polyborosiloxane and silicone rubber and commonly used abrasives are silicon carbide, aluminum oxide, boron carbide and polycrystalline diamond. Many researchers have tried to develop alternative AFM media apart from commercially available media from Extrude Hone Corporation and Kennametals to meet their requirement and to study the media characterization. Table 2 shows the development of the abrasive media by various researchers.

Table 2. Various types of abrasive media

Sl. No.	Authors	Polymer carrier	Abrasives & mesh size	Abrasive concentration	Media characterization	Remarks
1.	Wang et al. [21]	a) Silicone Rubber (P-Silicone) b) Silicone Rubber with Additives (A-Silicone)	SiC (Different mesh size)	50 %	NA	• Surface finish increased with A-Silicone Abrasive media
2.	Kar et al. [22]	a) Natural Rubber (NR) b) Butyl Rubber	SiC (Different mesh size)	68 %	Rheological properties	• Butyl Rubber based media shows good performance
3.	Kar et al. [23]	a) Natural Rubber b) Ethylene Propylene Diene Monomer (EPDM) c) Butyl Rubber (IIR) d) Silicone (Si) Rubber e) Styrene Butadiene Rubber (SBR)	SiC (Different mesh size)	68 %	Mechanical properties Rheological properties	• SBR based media shown good performance • Developed media are mechanically more stable than commercial media • Finishing is also depends on the carrier media
4.	Sankar et al. [24]	a) Styrene-Butadiene Rubber (SBR)	SiC	NA	Rheological properties	• Rheological properties of media affects the MRR and surface finish

4. Modeling and Optimization

To understand the complexity of the process it is necessary to construct a model either mathematical or simulation to study the effect of various process parameters on the output responses – surface finish and material Removal Rate (MRR). The model in general provides the information, which gives an insight into the nature of the phenomenon occurring in the real life situation. In this section, the main research findings on modelling and optimization of process parameters are listed below.

Petri et al. [25] developed the predictive process modeling to determine the set of process parameters effects on surface finish. It consists of set of neural networks models that predict the process behavior. The process parameters are characterized in five categories- workpiece parameters, media characteristics, machining parameters, technical specification and process objectives. This model mainly reduces the development time for new applications of the process and gives the information on effect of input variables on output parameters. Jain et al. [26] developed a Finite Element Model (FEM) to evaluate the stresses and forces developed during the machining process. A theoretical approach is also proposed in the paper to estimate the MRR and surface finish during the machining process. The theoretical results are compared with the available literature on experimentation and they are found to agree well with the published literatures. Jain et al. [27] evolved a versatile simulation model to predict surface roughness and MRR with reference to the abrasive size and concentration. The predicted results and RSM results are compared to understand the relative importance of AFM parameters. Jain et al. [28] proposed a model to determine the specific energy and tangential forces acting on AFM process based on five main parameters- grain size, applied pressure, hardness of workpiece, number of active grains and number of cycles. By considering the heat flows to the workpiece and medium, one dimensional heat transfer analysis has been carried out to determine the change in temperature of the workpiece. A FEM has been developed by Jain et al. [29] for analyzing the flow of viscoelastic polymer and the results obtained have been used to determine the MRR and roughness values. Theoretical results are compared with the experimental results. The central composite rotatable design is used to plan the experiments to reduce the number of experiments. For prediction of the active grain density, the concept of stochastic methodology introduced by Jain et al. [30] which generates and statistically evaluates the interaction between the abrasive grains and the workpiece surface. They have concluded that the grain density increases with increase in mesh size and abrasive concentration. Tavoli et al. [31] first time introduced a Group Method of Data Handling (GMDH)-type neural networks and generic algorithms for modelling of the effects of number of cycles and abrasive concentration on both MRR and surface finish. These neural network models are then used for multi objective Pareto-based optimization of AFM considering two conflicting objectives such as MRR and surface finish. Combination of GMDH-type neural network modelling and multi-objective Pareto optimization approach is very promising in discovering useful and interesting design relationships. Taguchi's parameter design strategy has been applied to investigate the effect of process parameters of centrifugal force-assisted AFM process on MRR and surface roughness by Walia et al. [32]. Mali and Manna [33] used Taguchi experimental quality design concept L_{18} ($6^1 \times 3^7$) mixed orthogonal array to determine the S/N ratio and to optimize the AFM process parameters. Analysis of Variance (ANOVA) and F test values indicate the significant AFM parameters affecting to the finishing performance. Uhlmann et al. [34] developed material model for visco-elastic abrasive medium used in AFM process using standard Maxwell model and Generalized Maxwell model by assuming the material removal is being caused by shear stress dependent on bonding of the abrasive grains. These models are validated with experimental results.

5. Applications of AFM

The various researchers are applied AFM technique for finishing various components used in-MEMS, industrial and biomedical to the required level of accuracy. The various applications of AFM process are presented in this section.

5.1 Machining of MEMS components

Micro channels are basic building blocks of microfluidic technology. Electron discharge machining process is commonly used to produce the micro channels but this process forms the recast layer in the machined area. Tzeng et al. [35] developed a self-modulating abrasive medium to remove the recast layer from the micro channels produced by wire-EDM. They have concluded, AFM process improves the quality of the channels by removing burrs, straightness, recast layer etc., with low cost and high efficiency. Miniaturized parts such as fuel injectors, micro filters, ink-jet printer nozzles, micro pumps possesses micro bores of diameter smaller than 500 μm in various sensors. To achieve the high quality of micro bore an inner wall polishing process are necessary and is achieved through AFM. Yin et al. [36] developed AFM technology to polish micro bores in metal- 400 and 500 μm bores in steel S45C, 500 μm bores in stainless steel and ceramics –304 and 260 μm bores in zirconia material.

5.2 Machining of industrial components

Bevel gear used in many diverse applications such as differential drives in automobile, rotorcraft drive system, locomotives, marine applications, railway track etc. These gears are commonly produced by conventional gear cutting methods or casting processes. After manufacturing of gears, finishing of gears is challenging task in many machining shop. Venkatesh et al. [37] introduced the Ultrasonically Assisted Abrasive Flow Machining (UAAFM) technique to finish bevel gears to maximum level. Ultrasonic frequency, extrusion pressure, time and media flows were considered as the input variables to improve the surface finish of bevel gears. Li et al. [38] applied AFM technology to improve the surface quality of nonlinear tube runner which is commonly used in some special passage exits of major parts in the field of military and civil. They have concluded this AFM technology is significant in improving surface integrity of the non-linear tube runner by removing burrs of cross hole, reducing stress concentration and enhancing reliability of parts. Jung et al. [39] studied the quality of Direct Injection (DI) diesel engine fuel injector nozzles finished by AFM process. The impact of the process on the engine performance and emissions are also assessed with DI diesel engine test setup. Improved quality of the nozzle characteristics are found in AFM processed injectors resulting in enhancement of engine performance and improved emissions. Kim et al. [40] developed AFM process for the deburring of chrome-molybdenum spring collets to remove the burrs generated during machining process. Xu et al. [41] finished the burrs present at the interaction between the tooth surface and the end surface of the helical gears to improve the quality of helical gears by using AFM process. The surface of the helical gear machined before and after AFM process is shown in Fig. 11 (a). Kenda et al. [42] carried out the finishing experiments on gear injection mold made of heat treated tool steel using AFM process. Santhosh and Somashekhar [43, 44] developed prototype abrasive model for finishing of hydraulic components such as nitroalloy collar and brass convergent divergent nozzle. The components are as shown in Fig. 11 (b) and (c).

5.3 Machining of bio-medical components

Freeform surfaces are widely used in biomedical, aerospace, turbine blades, automobile and optical components. These surfaces are commonly manufactured by rapid prototyping, casting and advanced CNC machines. After machining, finishing of these surfaces to higher level is a difficult task and many researchers are developed different types of finishing process. Sidpara et al. [45] finished knee joint implant by using magnetorheological fluid-based finishing tool. Kumar et al. [46] developed Rotational-MagnetoRheological Abrasive Flow Finishing (R-MRAFF) for finishing of freeform component similar to knee joint implant to nanometer level. Fig. 11 (d) shows the knee joint implant before and after finishing through AFM process.

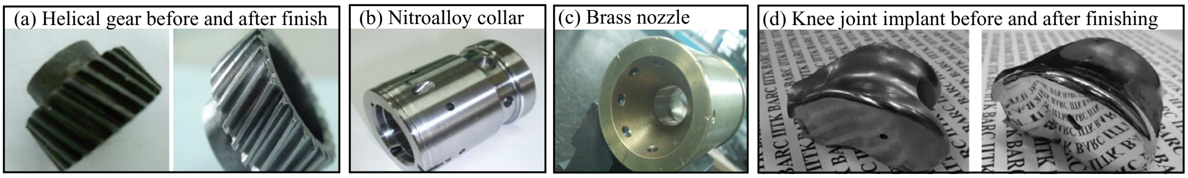


Fig. 11. Machined features through AFM process [41, 43, 44, 46].

7. Conclusions

Abrasive Flow Machining (AFM) process uses semi-solid medium consisting of visco-elastic polymer reinforced with abrasive particles are extruded under pressure through or across the surface to be finished. In the present article an attempt has been made to review the published technical papers on AFM process and papers are segregated into four categories - experimental setups, abrasive media, modeling and optimization and applications of AFM process. Following conclusions are drawn from the above review.

- Some of the developed experimental setups by various scholars are detailed in the paper. These setups includes:
  - Magneto Abrasive Flow Machining (MAFM); Magnetorheological Abrasive Flow Finishing (MRAFF); Centrifugal Force Assisted Abrasive Flow Machining (CFAAFM); Electro-Chemical aided Abrasive Flow Machining (ECAFM); Drill Bit Guided-Abrasive Flow Finishing (DBG-AFF); Rotational-Abrasive Flow Finishing (R-AFF); Ultrasonic Assisted Abrasive Flow Machining (UAAFM) and Rotational Magnetorheological Abrasive Flow Finishing (R-MRAFF)
- Media development usually uses the available polymer media are polyborosiloxane and silicone rubber and commonly used abrasives are silicon carbide, aluminum oxide, boron carbide and polycrystalline diamond.
- Modeling and optimization techniques are developed and used to study the output responses- MRR and Surface finish. The most commonly used techniques are ANOVA, Taguchi, Central composite design, Neural network, GMDH and pareto based optimization techniques, Mathematical, FEM techniques.
- This process is successfully applied to finish the components with intricate profiles mainly used in automotive, aerospace and biomedical fields.

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